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Assessment of Design Safety Limits for Fuel Cladding Based on Benchmark Tests

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Abstract

The PFBR core, which is highly enriched, is very compact due to neutronic considerations. The gap provided for coolant flow is so less that deformation of the clad will disturb the coolable geometry, which may lead to severe damage to the core. If adjacent pins balloon at the same axial level (coherent ballooning) they may touch each other impeding a proper flow of the coolant. To make the reactor commercial, studies are being made to exploit the D9 material at high burn up, longer cycle life and high temperature operations. The Design Safety Limits (DSLs) for fuel clad are given based on rupture. It is necessary to experimentally investigate and confirm the available margin at all category events, and to know at what conditions, the strain within the clad will affect the coolable geometry. Out of pile tests have been conducted with single fuel pin at high temperature and high pressure, to study the material behavior, to quantify and evaluate the available margin for the PFBR clad tube under various category events. The experimental facility has been indigenously developed to simulate the various category events. High sensitivity X-ray radiography method is deployed to measure the deformation of the specimen.

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Keywords: Ballooning; creep; design safety limits (DSL); x-ray radiography; clad, D9 SS

1. Introduction

The spacing of Prototype Fast Breeder Reactor (PFBR) fuel rods is such that on ballooning, the adjacent rods will touch; the key question is thus whether strains of this magnitude or greater can occur in practice in adjacent rods at the same level in the assembly. The associated question is how coolability is affected by large strains leading to progressive blockage of the coolant sub-channels. A conservative approach to prevent clad ballooning may reduce the operational envelope of the reactor, and in particular limit the burn-up. It is therefore of primary importance to understand the real transient behavior of fuel pin ballooning by carrying out experiments.

An experimental facility has been indigenously developed to simulate the various category events. Out of pile tests have been conducted with single fuel pin at high temperature and high pressure to get the photography

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of the evolution of deformation of the clad using high sensitivity X-ray radiography method. It can be further visualized, modeled or experiments can be conducted to get the scenario with multiple pins. The reason for conducting out of pile test is that ballooning takes place in the beginning of cycle, when irradiation is very less and the material is ductile. At the end of the life, the material becomes brittle due to irradiation and the concern will be rupture and ballooning will no more be of concern. The details of these experimental activities and the results have been presented in this paper.

2. Studies on ballooning

In PFBR, the core temperature may rise locally due to Loss Of Flow Accident (LOFA), Primary Sodium Pump (PSP) trip, seizure or rupture, sodium voids, or any kind of loss of heat removal from the fuel pin. At this condition the clad tube can suddenly undergo large circumferential deformation. This type of behavior of fuel clad tube is reported as ballooning [1]. Materials like polymers; rubber etc. generally exhibit this behavior. This phenomenon is also seen in metals at high temperatures.

During transients, the clad temperature increases. This results in increase in internal pressure, thus increase in hoop stress. Ballooning is likely to take place at a temperature when the increased hoop stresses are greater than the Ultimate Tensile Strength (UTS) of the clad at that temperature. Thus, ballooning of the cladding occurs due to an increase in the internal pressure of the fuel pin and also due to the decrease in the cladding strength [2]. The most serious result from clad ballooning is that it may cause the blockage of the flow channels and result in a permanent restriction of the coolant flow. A coolant flow restriction results in an increase in the cladding and fuel temperatures resulting in severe fuel damage, since it is found that coolability will be affected if there is extensive clad melting. Figure.1 and Figure.2 show the flow obstruction due to ballooning in square fuel pins lattice.

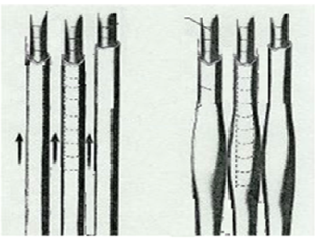

Fig. 1. Clad ballooning

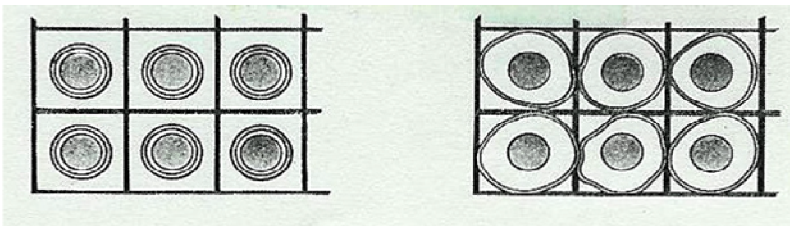

Fig. 2. Clad ballooning obstructing flow in a square fuel pins lattice.

It is observed that the unirradiated fuel pins fail after ballooning late in the transient when the cladding temperature was high [3]. The failure of the cladding in these tests was ductile, and it was a burst opening. The used fuel fails early in the transient with brittle fracture which was a longitudinal crack.

3. Ballooning in prototype fast breeder reactor (PFBR)

3.1. Spacing of PFBR fuel rods

The fuel pin is 6.6 mm on the outer diameter and the thickness of the cladding tube is 0.45 mm. The pins are spaced by helically winding a wire of 1.65 mm diameter. Considering pressure drop, mixing and vibration, 200 mm spacer wire pitch has been chosen. The nominal pin pitch in the bundle is 8.28 mm with a nominal clearance of 0.03 mm.

3.2. Design safety limits for fuel pins

Design Safety Limits (DSL) has been defined in order to assess that the design provisions of the system/components are adequate to ensure safety.

For temperature limits concerning the clad, the criterion is to retain its integrity. The clad material is subjected to stresses and operating at high temperatures and hence undergo damage. The damage is from creep considerations. Hence, for defining temperature limits, Cumulative Damage Fraction (CDF) approach is followed for which structural design criteria for highly irradiated components and data on material behavior under transients are very important. Since the limits are on the basis of damage, time duration has to be defined.

The recommended temperature limits for all category and time durations are as follows:

Category 1: 973 K and CDF $\leq$ 0.25
Category 2: 974 – 1023 K for 75 min and
1023 – 1073 K for 15 min and CDF $\leq$ 0.25
Category 3: 974 – 1023 K for 15 min and
1023 – 1073 K for 6 min and
1123 – 1173 K for 2 min and CDF $\leq$ 0.25
Category 4: 1473 K

4. Experimental investigations

A High Temperature Clad Tube Test facility (HTCTTF) has been indigenously developed to study ballooning at various operating conditions. The details of the test facility are given below.

4.1. High temperature clad tube test facility (HTCTTF)

The test facility consists of a stainless steel pressure vessel designed to withstand up to 150 bars pressure, D9 clad tube and electric furnace held together by the stand. Three adapters are fitted on the pressure vessel for pressure gauge, safety valve, and a relief valve. The experimental setup is shown in Figure.3.

The clad tube is 32 cm long and 6.6 mm diameter, with a thickness of 0.45 mm and is welded to the pressure chamber. It is filled with argon gas at high pressure, to simulate the fission gas pressure. The closed tube under internal pressure facilitates biaxial state of stress in the clad tube. The furnace is positioned such that length of 50 mm of the fuel pin is heated to the maximum temperature and the heat transfer to the weld is negligible. The furnace is 150 mm long and has 200 mm outer diameter and 10 mm inner diameter. It is designed to withstand high temperature (up to 1200 ^{0}C) for the desired period uninterruptedly with high heating rate (up to 200 ^{0}C/minute). This set up is insulated by ceramic wool. This is coupled with a PID Controller along with a Silicon Controlled Resistor (SCR), to achieve the exact temperature required.

High intensity X-Ray system is deployed for the online-monitoring of the clad ballooning inside the furnace. X-ray images can be taken at desired interval without disturbing the experimental set up and operating conditions.

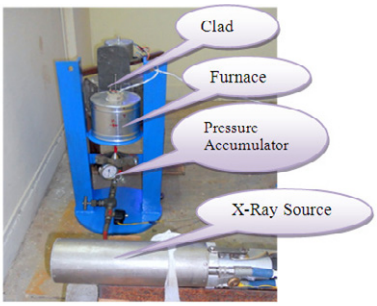

Fig. 3. Experimental set up

4.2. Experiment conducted to verify category 1 limit

This experiment is an accelerated test conducted to simulate the category-1 event condition, which is the normal operating condition. The normal operating conditions are 700 °C temperature, 60 bars pressure and time to rupture is 540 days. The experiment is accelerated using Larson Miller Parameter (LMP) and hence, it is conducted at 970 °C (1243 K), and the minimum life expected is 2 hours. Figure 4 shows the strain curve. It can be observed that there is only 2.1 % dilation at the end of 3.5 hours. No ballooning is observed up to 3.5 hours.

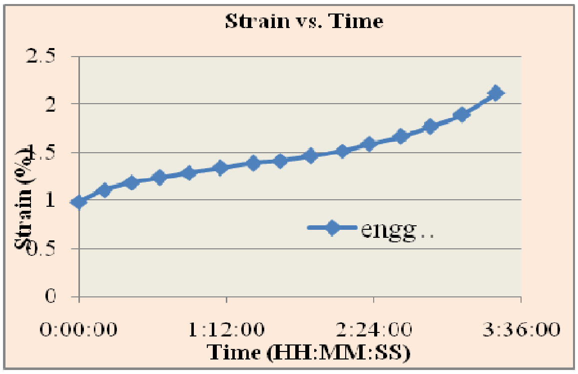

Fig . 4. Before Ballooning at 970 °C and 60 bars

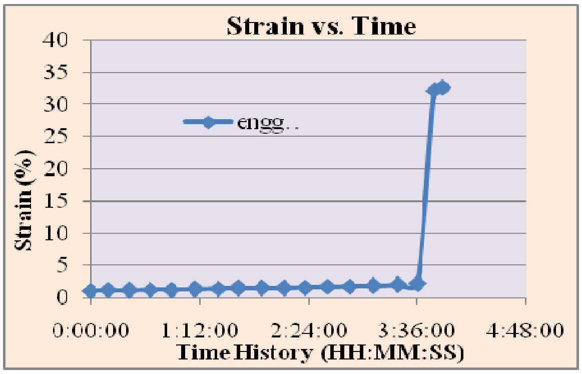

Fig. 5. Ballooning observed

Figure.5 shows sudden increase in the diameter from 2.1 % to 32 %. This sudden, large deformation, termed as ballooning is observed after 3.5 hours. It is also observed that rupture has taken place 10 minutes after ballooning. Thus from this we can conclude with high confidence that the coolable geometry will be maintained during normal operating conditions of the reactor.

These experimental results can be used as a basis to find the margin available in category-2 and category-3 events using Larson Miller Parameter (LMP), which is given by

$$LMP = T\,(C + \log_{10} t_r)$$

where C is a material constant (C = 13.5 for D9 material), T- Temperature in K and t_r is time to rupture (t_r = 3.5 hours).

$$LMP = 1243\,(13.5 + \log 3.5) = 17456.77$$

Category 2 limits:

T = 800 °C = 1073 K, allowable time t_r = 15 minutes = 0.25 hours

$$LMP = 17456.77 = 1073\,(13.5 + \log t_r')$$

Thus the time to rupture t_r' = 587.65 hours.

The available margin is t_r / t_r' = 0.25/587= 4.254 * E-4, which is very less.

Hence there is enough margin available for ballooning under category-2 event.

Category 3 limits:

T = 900 °C = 1173 K, allowable time t_r = 2 minutes = 0.033 hours

$$LMP = 17456.77 = 1173\,(13.5 + \log t_r')$$

Thus the time to rupture t_r' = 24.1 hours.

Therefore, the Cumulative Damage Fraction (CDF) is t_r / t_r' = 0.033/24.1 = 1.36 * E-3 which is very less. Hence there is enough margin available for ballooning under category-3 event. The results are summarized in Table 1.

Table 1. Margin available for Ballooning at various category events.

Category	Temp (^oC)	DSL Time limit (t_r) hours	(t_r') from LMP calc (hours)	Margin (t_r / t_r')
1	700	2	3.5	0.57
2	800	0.25	587.65	4.25*E-4
3	900	0.033	24.1	1.36*E-3
4	1200	No time limit – Rupture is allowed		

4.3. Experiment conducted to verify category 4 limit at different heating rates

Under category 4 event, fuel failure is permitted but radioactivity limits will be adhered. Safety objective in this case is to maintain coolability of the SA. A logical examination of coolability requirements, and the transient experiences indicates that coolability will be maintained if extensive clad melting is avoided. Hence, philosophy adopted is to ensure coolable geometry rather than clad integrity. Limit relating to melting point of clad is adequate. With margin of over 200 K, limit of 1473 (1200 ^0C) has been adopted.

High temperature experiments have been conducted for the clad tube at 60 bar pressure, which is the maximum operating pressure of the PFBR clad tube, to simulate the category 4 event criteria. The maximum temperature limit of category 4 event is 1200 ^0C. The experiment has been conducted for two specimens for different heating rates. The first specimen has been heated to 1200 ^0C for a heating rate of 100 K/min and the second specimen has been heated to 1200 ^0C for a heating rate of 40 K/min.

Figure 6 and Figure 7 show the temperature evolution under category-4 condition for fast heating and slow heating respectively. During the fast heating rate (specimen-1), small leak is found at the temperature of 750 ^oC (pressure drop to 55 bar) and at 1200 ^oC (pressure drop to 40 bar). The subsequent deformation of the clad tube is shown in Figure.6b. In case of the slow heating rate (specimen-2) the specimen ruptured 2 minutes after attaining the desired temperature of 1200 ^oC. The ballooning of the clad tube and crack is shown in Figure.7b. The maximum deformation observed during the fast heating rate is 7.8 mm and during the slow heating rate is 8.51 mm. But the crack found in the slow heating rate was large, when compared to the small leak observed during fast heating.

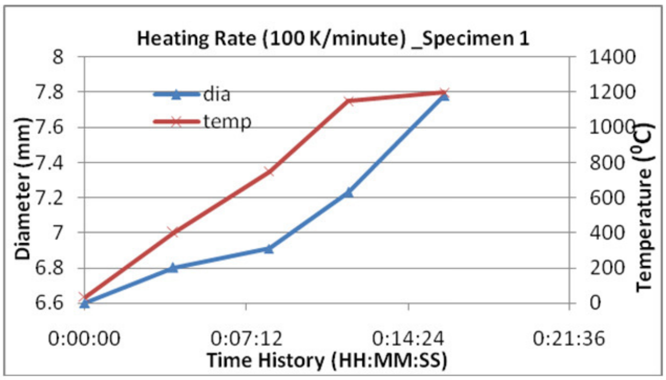

Fig. 6a.Specimen–1:Experiment conducted for category-4 event (fast heating)

Fig. 6b. Leak observed..

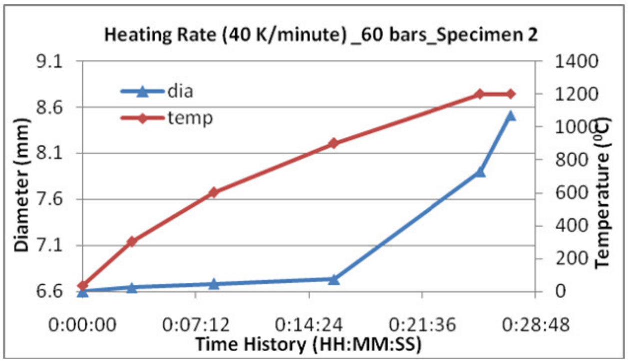

Fig. 7. Specimen - 2: Experiment conducted for category-4 event (slow heating)

Fig. 7b.Leak observed.

The actual heating rate during an enveloping event of category-4 event, i.e. primary pipe rupture is 100 K/s. It can be inferred from the experiments that the clad ruptures before ballooning during fast heating. The DSL for category-4 events allows clad rupture, but ballooning is not acceptable. Hence, the coolable geometry will not be affected during fast heating, which satisfies the DSL. However, more experiments are to be conducted for acquiring greater confidence in the results and to find the margin available in category-4 event.

5. Conclusions

Based on limited tests carried out at high temperature, a few new and interesting results have been obtained on rapid deformation behavior of fuel claddings. The tests exhibit phenomenon of ballooning at the beginning of life of the core. The whole deformation properties obtained at various time intervals provide important data for the development of constitutive models for the material. Further, tests are in progress to identify the zones where either clad would rupture or clad would undergo ballooning. This information adds new insight into mechanics of deformation and failure of structures at high temperature.

Acknowledgements

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